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## Stellar Exotica produced from Stellar Encounters

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**Abstract.** The importance of stellar encounters in producing stellar exotica in dense stellar clusters is reviewed. We discuss how collisions between main-sequence stars may be responsible for the production of blue stragglers in globular clusters. We also discuss the possible pathways to the production of X-ray binaries, cataclysmic variables, and millisecond pulsars in globular clusters. Neutron stars in globular clusters are likely to exchange into binaries containing moderate-mass main-sequence stars, replacing the lower-mass components of the original systems. These binaries will become intermediate-mass X-ray binaries (IMXBs), once the moderate-mass star evolves off the main-sequence, as mass is transferred onto the neutron star possibly spinning it up in the process. Such systems may be responsible for the population of millisecond pulsars (MSPs) that has been observed in globular clusters. Additionally, the period of mass-transfer (and thus X-ray visibility) in the vast majority of such systems will have occurred 5 – 10 Gyr ago thus explaining the observed relative paucity of X-ray binaries today, given the large MSP population.

### 1. Introduction

Stellar clusters are ubiquitous. Globular clusters contain some of the oldest stars, whilst the youngest stars are found in OB associations or in other clusters associated with recent star formation. Such crowded places are hostile environments: a large fraction of stars will collide or undergo close encounters. Wide binaries are likely to be broken up, whilst tighter ones will suffer major perturbations and possibly collisions from passing stars. Hydrodynamical computer simulations of such encounters play a vital role in understanding how collisions will affect the evolution of stellar clusters and produce the myriad of stellar exotica seen such as X-ray binaries, blue stragglers and millisecond pulsars. The cluster of stars at the centre of a galaxy may provide the material to form a massive black hole and fuel it as a quasar. Encounters in very young clusters will influence the fraction of stars contained in binaries and their nature. Such encounters will affect the stellar population of the entire galaxy as all stars are formed in clusters.

In this review, we consider the importance of stellar encounters within globular clusters, where collisions between two main-sequence stars may produce blue stragglers. Encounters involving neutron stars and non-compact stars may help explain the large population of millisecond pulsars. In §2 we compute the

timescales for encounters in dense stellar clusters. In §3 the importance of such encounters is discussed. Encounters in globular clusters are considered in §§4, 5, and 6, where we discuss blue stragglers, low-mass X-ray binaries, and cataclysmic variables, respectively. A summary of this review is given in §7.

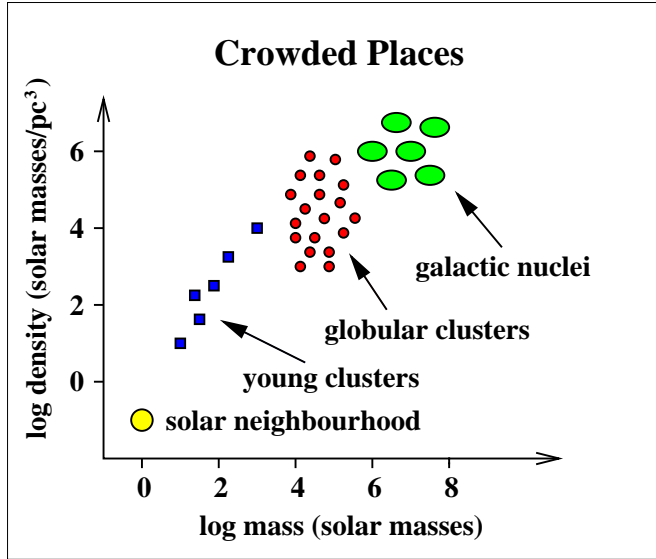


Figure 1. A schematic diagram of crowded places

## 2. Encounter Timescales

Encounters between two stars will be extremely rare in the low-density environment of the solar neighbourhood. However, in the cores of globular clusters, and galactic nuclei, number densities are sufficiently high ( $\sim 10^5$  stars/pc<sup>3</sup> in some systems, as shown in Figure 1) that encounter timescales can be comparable to, or even less than, the age of the universe. In other words, a large fraction of the stars in these systems will have suffered from at least one close encounter or collision in their lifetime.

The cross section for two stars, having a relative velocity at infinity of  $V_\infty$ , to pass within a distance  $R_{\min}$  is given by

$$\sigma = \pi R_{\min}^2 \left( 1 + \frac{V^2}{V_\infty^2} \right) \quad (1)$$

where  $V$  is the relative velocity of the two stars at closest approach in a parabolic encounter (*i.e.*  $V^2 = 2G(M_1 + M_2)/R_{\min}$ , where  $M_1$  and  $M_2$  are the masses of the two stars). The second term is due to the attractive gravitational force,

and is referred to as gravitational focussing. In the regime where  $V \ll V_\infty$  (as might be the case in galactic nuclei with extremely high velocity dispersions), we recover the result,  $\sigma \propto R_{\min}^2$ . However, if  $V \gg V_\infty$  as will be the case in systems with low velocity dispersions, such as globular clusters,  $\sigma \propto R_{\min}$ .

One may estimate the timescale for a given star to undergo an encounter with another star,  $\tau_{\text{coll}} = 1/n\sigma v$ . For clusters with low velocity dispersions, we thus obtain

$$\tau_{\text{coll}} = 7 \times 10^{10} \text{yr} \left( \frac{10^5 \text{pc}^{-3}}{n} \right) \left( \frac{v_\infty}{10 \text{km/s}} \right) \left( \frac{R_\odot}{R_{\min}} \right) \left( \frac{M_\odot}{M} \right) \text{ for } v \gg v_\infty \quad (2)$$

where  $n$  is the number density of single stars of mass  $M$ . For an encounter between two single stars to be hydrodynamically interesting, we typically require  $R_{\min} \sim 3R_\star$  (see for example, Davies, Benz & Hills 1991). We thus see that for typical globular clusters, where  $n \sim 10^5$ , up to 10% of the stars in the cluster cores will have undergone a collision at some point during the lifetime of the cluster.

We may estimate the timescale for an encounter between a binary and a third, single star, in a similar manner where now  $R_{\min} \simeq d$ , where  $d$  is the semi-major axis of the binary. The encounter timescale for a binary may therefore be relatively short as the semi-major axis can greatly exceed the size of the stars it contains. For example, a binary with  $d \sim 1\text{AU}$  (ie  $216 R_\odot$ ), will have an encounter timescale  $\tau_{\text{enc}} \ll 10^{10}$  years in the core of a dense globular cluster. Thus encounters between binaries and single stars may be important in stellar clusters even if the binary fraction is small.

Encounters between single stars and extremely wide binaries will lead to the break up of the binaries as the kinetic energy of the incoming star exceeds the binding energy of the binary. Such binaries are often referred to as being *soft*. Conversely, *hard* binaries will be resilient to break up. Encounters between single stars and hard binaries have three main outcomes as shown in Figure 2. A fly-by may occur where the incoming third star leaves the original binary intact. However such encounters will harden (ie shrink) the binary, and alter its eccentricity. Alternatively, an exchange may occur where the incoming star replaces one of the original components of the binary. During the encounter, two of the stars may pass so close to each other that they merge or form a very tight binary (as they raise tides in each other). The third star may remain bound to the other two as indicated in outcomes d), e) and f) in Figure 2.

The cross section for a single star to pass within a distance  $R_{\min}$  of the center of mass of a binary is given by  $\sigma = \pi R_{\min}^2 (1 + V_c^2/V_\infty^2)$ , where  $V_\infty$  is the relative speed at infinity, and  $V_c$  is the relative speed at which the system has zero total energy and is given by  $V_c^2 = F(M_1, M_2, M_3)/d = GM_1 M_2 (M_1 + M_2 + M_3)/M_3 (M_1 + M_2) d$ , where  $M_1$  is the mass of the primary,  $M_2$  the mass of the secondary and  $M_3$  is the mass of the incoming, single star. For hard binaries, where  $V_c \gg V_\infty$ , the exchange cross section can be written as

$$\sigma_{\text{ex}} = k_{\text{ex}}(q_1, q_2) \pi d^2 \cdot \frac{GM_1 F(q_1, q_2)}{d} \cdot \frac{1}{V_\infty^2} \quad (3)$$

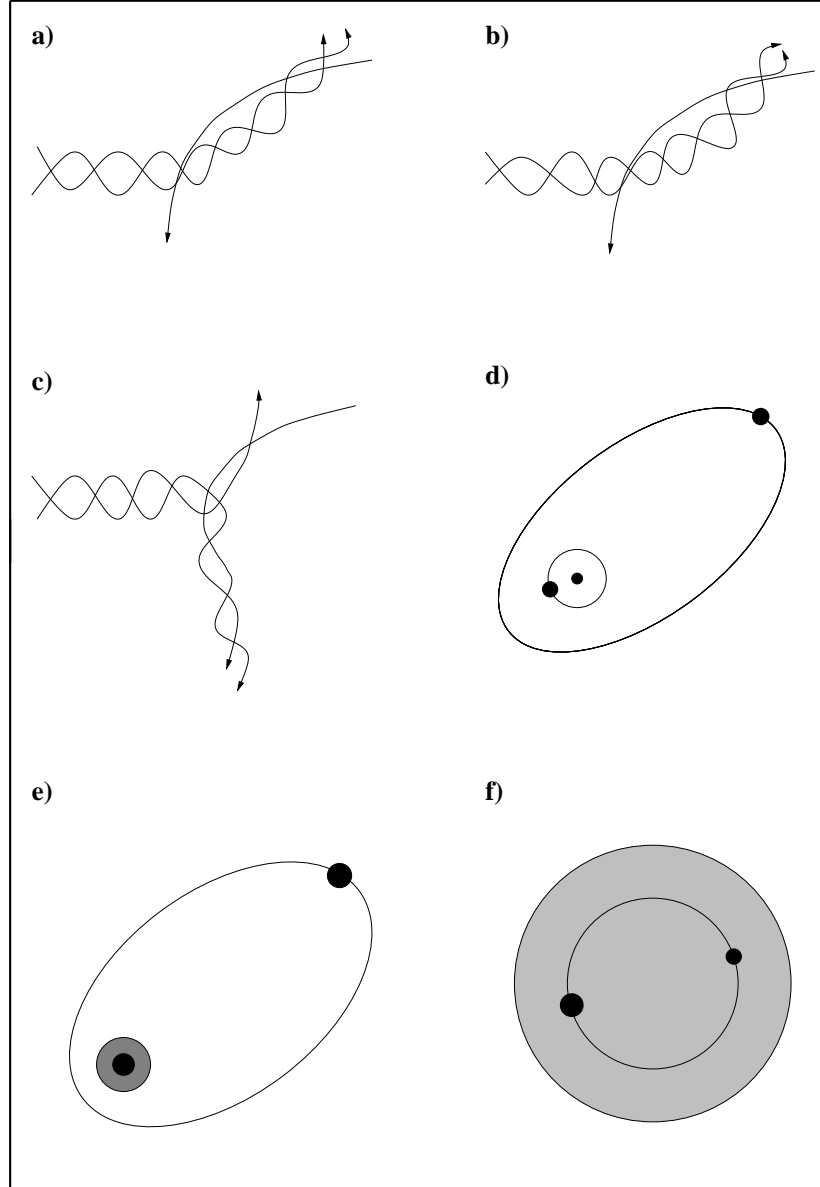


Figure 2. The possible outcomes of encounters between binaries and single stars: a) a fly-by, b) a scattering-induced merger where a fly-by leads to a merger of the two stars in the binary, c) an exchange, d) a triple system, e) a merged binary where two stars have merged and remains bound to the third star, and f) a common envelope system where the envelope of the merged star engulfs the third star.

where  $q_1 = M_2/M_1$ ,  $q_2 = M_3/M_1$ , and  $F(q_1, q_2) = q_1(1 + q_1 + q_2)/q_2(1 + q_1)$ . The constant  $k_{\text{ex}}(q_1, q_2)$  has to be determined through numerical simulations.

Similarly, one may write an expression for the cross section for fly-by encounters, where the components of the binary remain unchanged, but the binary is hardened by some amount.

$$\sigma_{\text{fb}} = k_{\text{fb}}(q_1, q_2)\pi d^2 \cdot \frac{GM_1 F(q_1, q_2)}{d} \cdot \frac{1}{V_\infty^2} \quad (4)$$

where again  $k_{\text{fb}}(q_1, q_2)$  has to be determined through numerical simulations.

One may also compute the cross section for two of the three stars to pass within some minimum distance,  $R_{\text{min}}$ , during an encounter. Hut & Inagaki (1985) found that such a cross section can be written in the following form,

$$\sigma_{mb} = k_{\text{rmin}}(q_1, q_2)\pi d^2 \frac{GM_1 F(q_1, q_2)}{d} \cdot \frac{1}{V_\infty^2} \left( \frac{R_{\text{min}}}{d} \right)^\gamma \quad (5)$$

where both  $k_{\text{rmin}}$  and  $\gamma$  can be found through simulations of encounters. For encounters involving three identical stars,  $\gamma \sim 0.5 - 1$ .

The most likely outcome of an encounter between a single star and a wide (though hard) binary is either a fly-by or an exchange. Such an event will harden the binary by  $\sim 20\%$ . After a number of these encounters the binary will therefore be very much smaller and consequently the relative probability of some variety of merger occurring during later encounters will be enhanced. For example, binaries containing solar-like stars which are just resilient to breakup in a typical globular cluster have initial separations  $d \sim 1000R_\odot$  but will have separations  $\sim 50 - 100R_\odot$  today (see for example Davies & Benz 1995).

In encounters between two binaries, we again require the two systems to pass within  $\sim d$  of each other. Hence binary/binary encounters will dominate over binary/single encounters only if the binary fraction is  $\geq 30\%$ . Unfortunately, the binary fraction in many stellar clusters is not well known.

### 3. Importance of Collisions in producing Stellar Exotica

Thus far we have seen that collisions and tidal encounters between two single stars will occur in the cores of globular clusters and that encounters involving binaries will occur both in globular and open clusters. These encounters will be important for a number of reasons. They may produce the various *stellar exotica* that have been seen in clusters such as blue stragglers and millisecond pulsars. Stellar encounters will also have a role in the dynamical evolution of clusters. Stellar collisions in clusters may also lead to the production of massive black holes. Once produced, these black holes may be fed by the gas ejected in subsequent stellar collisions.

Given that each star involved in a collision may be either a main-sequence star (MS), a red giant (RG), a white dwarf (WD), or a neutron star (NS), there are ten distinct combinations of collision pairs as shown in Figure 3. In this review we will consider encounters involving two main-sequence stars, and encounters involving a red giant or main-sequence star and a compact star

(*i.e.* either a white dwarf or a neutron star). Encounters between two main-sequence stars may be responsible for the observed population of blue stragglers within globular and open clusters, as will be discussed in a later section. Those involving compact objects and red giants or main-sequence stars may produce interacting binaries where material is transferred from the larger donor onto the compact object. Examples of interacting binaries include low-mass X-ray binaries (LMXBs) and cataclysmic variables (CVs) and both classes of objects will be considered in subsequent sections.

	MS	RG	WD	NS
MS	BS		Interacting	
RG			Binaries	
WD				
NS				GRB

Figure 3. The various possible collisions between two stars.

Merging neutron stars have been suggested as the source of gamma-ray bursts (GRBs). A direct collision between two neutron stars is extremely unlikely. However, tight neutron-star binaries might be produced through the evolution of binaries, including those that have been involved in encounters with other stars. The neutron stars in such tight binaries may then ultimately merge as they spiral together as angular momentum and energy is emitted in the form of gravitational radiation. The event rate of such mergers may therefore be enhanced within dense clusters. We will not consider such mergers further in this review.

#### 4. Blue Stragglers

Blue stragglers are positioned on the upper end of the main-sequence beyond the present day turn-off mass. They have been observed in many globular clusters, including:  $\omega$  Cen (Kaluzny et al. 1997), 47 Tuc (Paresce et al. 1991), NGC 6397 (Auriere et al. 1990), M30 (Yanny et al. 1994, Guhathakurta et al. 1996), and M80 (Ferraro et al. 1999). These stars may have formed from the merger of two lower-mass main-sequence stars either in an encounter between two single stars or in encounters involving binaries when two main-sequences collide and merge as part of the encounter. The fraction of blue stragglers in binaries may therefore be an important diagnostic for the binary fraction for globular clusters.

Simulations of collisions between two main-sequence stars have been performed by many groups, most using the method known as Smoothed Particle Hydrodynamics (SPH). SPH is a lagrangian method where the fluid is modelled as an ensemble of particles which follow the flow of the fluid. Computational resources are not wasted in following the evolution of the voids, such as the gaps between two colliding stars, and the resolution can vary in a natural way; more particles being found in the places of most interest. Because SPH has no specific need for a computational box, we are able to follow the flow of gas completely. Thus we do not experience the Columbus Effect, where material is lost off the edge of a computational domain.

For a given value of the relative velocity,  $V_\infty$ , between the two stars, one may compute how close the stars have to pass in order for a capture to occur. Even closer encounters will produce a single, merged object. Simulations yield values for the capture radius,  $R_{\text{capt}} \sim 3R_{\text{ms}}$ , and provide a lower limit for the merger radius of  $R_{\text{merg}} \sim 2R_{\text{ms}}$ . The mass lost from the system on the initial impact is small, typically  $M_{\text{lost}} \leq 0.01M_{\text{ms}}$ . Early work suggested that the merged stars would be well mixed (Benz & Hills 1987, 1992). Subsequent simulations, using a more centrally concentrated model for the main-sequence stars, seem to suggest that the material in the cores will not (at least initially) mix with the envelope gas (Lombardi, Rasio & Shapiro 1995). More recently, the subsequent evolution of the merged objects has been considered and theoretical distributions on a colour-magnitude diagram have been produced (Sills & Bailyn 1999). This study showed that the distribution of blue stragglers in M3 were difficult to reproduce using a single set of assumptions, however if three particular bright blue stragglers were neglected, the remaining population could have been produced in mergers of stars occurring in encounters between binaries and single stars. Extremely-high resolution SPH simulations of main-sequence star collisions are ongoing to study in more detail the internal structure of the merger products (see for example Sills et al. 2001).

## 5. X-ray Binaries and Millisecond Pulsars

Both millisecond pulsars (MSPs) and low-mass X-ray binaries (LMXBs) have been observed in relative abundance in globular clusters clearly indicating that their origin is related to stellar encounters. Under the standard model, MSPs are produced in LMXBs where the neutron star is spun-up as material is accreted from the Roche-filled companion. However observations suggest that there are far more MSPs than LMXBs which, given their comparable expected lifetimes, poses a problem for the standard model. One would therefore wish to investigate whether encounters may lead to other potential channels for MSP production which will not pass through a prolonged phase of X-ray emission.

Early work focussed on encounters between single neutron stars and either red giants or main-sequence stars. Fabian, Pringle & Rees (1975) suggested that such encounters would produce the observed X-ray binary population. Calculations of encounter rates suggest that encounters involving main-sequence stars will be more frequent than those involving red giants. Numerical hydrodynamic simulations of encounters between neutron stars and red giants or main-sequence stars revealed that the  $R_{\text{capt}} \sim 3.5R_\star$  for main-sequence stars, and

$R_{\text{capt}} \sim 2.5R_{\star}$  for red giants (Rasio & Shapiro 1991; Davies, Benz & Hills 1992, 1993). Consideration of the subsequent evolution of the two stars suggested a lower limit of  $R_{\text{merg}} \gtrsim 1.8R_{\star}$  in both cases. As all encounters in globular clusters are highly gravitationally focussed, the cross section for two stars to pass within a distance  $R_{\text{min}}$ ,  $\sigma_{\text{rmin}} \propto R_{\text{min}}$ . Hence approximately *half* of the bound systems will form binaries and the rest will form single merged objects. In the latter case encounters involving main-sequence stars will produce a thick-disk system with the shredded remains of the main-sequence star engulfing the neutron star. The equivalent encounters involving red giants will produce common envelope systems, where the red-giant envelope engulfs both the neutron star and the red-giant core.

Even if all the merged systems produced MSPs without passing through a prolonged X-ray phase, the expected MSP production rate is only a factor of  $\sim 2-3$  times larger than that for the LMXBs. The solution to the MSP enigma seems unlikely to lie with encounters involving single stars.

As was mentioned earlier, the binary fraction within globular clusters is highly uncertain. However, because of the larger cross section for encounters involving binaries, only a small fraction of binaries are required for binary-single encounters to be as important as encounters between two single stars. Calculation of the cross sections for fly-bys, exchanges, and mergers, lead to the predicted production rates for LMXBs and smothered neutron stars from encounters involving primordial binaries (Davies, Benz & Hills 1993, 1994; Davies & Benz 1995; Davies 1995). Although encounters today will produce smothered neutron stars, they also produce LMXBs in roughly equal numbers; the MSP production rate problem remains.

The solution may lie in considering the *past*. The idea (developed by Davies & Hansen [1998]) is shown in Figure 4. Exchange encounters will tend to leave the most massive stars within binaries, independent of the initial binary composition. When neutron stars exchange into these binaries, the less massive of the two main-sequence stars will virtually always be ejected. The remaining main-sequence star will typically have a mass of  $\sim 1.5-3M_{\odot}$ . The binary will evolve into contact once the donor star evolves up the giant branch.

The subsequent evolution of such a system will depend on the mass of the donor star and the separation of the two stars when the donor fills its Roche lobe. For example, it has been suggested that the system may enter a common envelope phase (eg Rasio, Pfahl & Rappaport 2000). Alternatively, the system may produce an *intermediate-mass X-ray binary (IMXB)*. In such a system the neutron star may accrete sufficient material (and with it, angular momentum), for it to acquire a rapid rotation (ie millisecond periods). Because the donors are all more massive than the present turn-off mass in globular clusters, all IMXBs will have undergone their mass transfer *in the past*. If these systems evolve into MSPs, then we obtain, quite naturally, what is observed today, namely a large MSP population and a relatively small X-ray binary population.

Observations and modelling of the X-ray binary Cygnus X-2, provide important clues in helping determine the subsequent evolution of intermediate-mass systems. This binary is unusual in that its donor has the appearance (by its position in an HR diagram) of a slightly-evolved  $3-5 M_{\odot}$  star, yet its measured mass is much lower ( $\sim 0.5 M_{\odot}$ ). The evolutionary history of Cyg X-2 has been



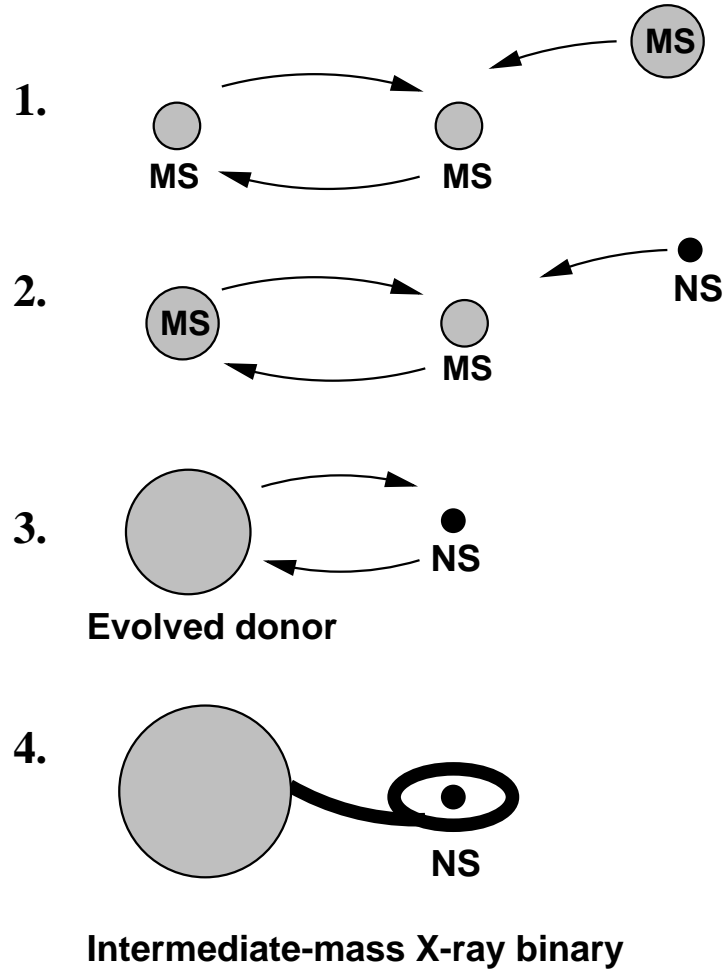


Figure 4. The evolutionary pathway to produce intermediate-mass X-ray binaries (IMXBs) in globular clusters (Davies & Hansen 1998). A more-massive main-sequence star exchanges into a binary containing two main-sequence stars (phase 1), a neutron star exchanges into the binary replacing the lower-mass main-sequence star (phase 2). The intermediate-mass star evolves off the main-sequence and fills its Roche Lobe (phase 3). The system has a relatively short phase as an IMXB (phase 4), possibly producing a millisecond pulsar.

considered (King & Ritter 1999, Podsiadlowski & Rappaport 2000, and Kolb et al. 2000). The unusual evolutionary state of the secondary today appears to indicate that the system has passed through a period of high-mass transfer from an initially relatively-massive star ( $\sim 3.6M_{\odot}$ ) which had just evolved off the main sequence. The neutron star has somehow managed to eject most of the  $\sim 2M_{\odot}$  of gas transferred at Super-Eddington rates from the donor during this phase. This evolutionary history may also apply to the IMXBs formed dynamically in globular clusters. Vindication of this model also comes from studying the dynamical evolution of the binary within the Galactic potential (Kolb et al. 2000). A suitable progenitor binary originating in the Galactic Disc has sufficient time, and could have received a sufficient kick when the primary exploded to produce a neutron star, to reach the current position of Cyg X-2.

## 6. Cataclysmic Variables

A cataclysmic variable (CV) comprises of a low-mass star in a binary with a white dwarf. The low-mass star is filling its Roche lobe and is transferring material onto the white dwarf via an accretion disc. CVs are thus the white-dwarf analogues of LMXBs. One might therefore imagine that the CV population within a globular cluster may be boosted in a similar fashion to the LMXB population. However detecting CVs in globular clusters has proved to be difficult, although a few clusters are now known to contain spectroscopically-confirmed CVs (for a review see Grindlay 1999). Ongoing surveys of a number of globular clusters using Chandra and XMM are also likely to boost the known population (see for example Cool et al., in these proceedings).

CVs might be produced via tidal encounters between white dwarfs and main-sequence stars (Verbunt & Meylan 1988). Calculations of encounters between binaries and single white dwarfs demonstrate that white dwarfs will exchange into primordial binaries producing CVs (Davies 1995; Davies & Benz 1995). CVs are also produced in primordial binaries without the outside interference of a passing single star. Indeed  $\sim 1\%$  of all binaries will produce CVs (de Kool 1992) by passing through the following stages. Beginning with two main-sequence stars in the binary, the primary will evolve off the main-sequence, expand up the giant branch and fill its Roche lobe. The subsequent mass transfer may be unstable and lead to the formation of a common envelope of gas around the red-giant core (which is essentially a white dwarf) and the secondary (which is still on the main sequence). This enshrouding envelope of gas will be ejected as the white dwarf and main-sequence star spiral together. If the initial separation of the two stars were too small, the main-sequence star and white dwarf will coalesce before all the envelope is removed, however under favourable initial separations, the entire common envelope can be removed leaving the white dwarf and main-sequence star in a tight binary (with a separation of a few  $R_{\odot}$ ). Such a binary will then come into contact if angular momentum loss mechanisms can work on sufficiently short timescales or when the main-sequence star evolves into a red giant. A CV will then be produced if the subsequent mass transfer is stable.

The formation route for *primordial CVs* (PCVs) described above will be *inhibited* in dense clusters if encounters with single stars or other binaries disturb

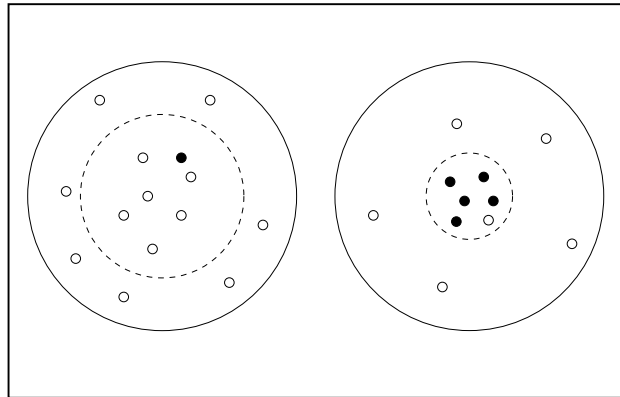


Figure 5. A schematic illustration of the CV population within a low-density (left) and high-density (right) globular cluster. The dashed circles denote the cores of the clusters. Filled circles are CVs formed dynamically, whilst open circles are primordial CVs (PCVs) which have formed from primordial binaries.

the PCV binary before the onset of the common-envelope stage (Davies 1997), for example an intruding third star may break up a wide binary. An interesting consequence is that PCVs are unlikely to be found within the cores of dense clusters, but will be found in their halos and throughout lower-density clusters. Conversely CVs formed via encounters between binaries and single stars are likely to be found exclusively in the cores (where the encounters will occur) and will be produced in greater numbers within higher-density clusters (Davies 1997) as is illustrated schematically in Figure 5.

## 7. Summary

We have reviewed stellar encounters in crowded places, considering their frequency and importance in producing the various exotic objects seen in clusters. Our conclusions are as follows

1. Encounters happen in crowded places, such as the cores of globular clusters, and galactic nuclei.
2. They may lead to the formation of various observed *stellar exotica*, such as blue stragglers.
3. Blue stragglers may be formed via mergers of lower-mass main-sequence stars.
4. Interacting binaries such as LMXBs and CVs will be produced via encounters between compact objects and either single stars or binaries.

5. The MSP population in globular clusters may have been produced from an earlier generation of *intermediate-mass X-ray binaries (IMXBs)*.

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